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13. ABSTRACT (Maximum 200 words)

Combining plan view information from aerial photography showing details of stream channels on desert pavement surfaces with process-based erosion models, a high-resolution, "synthetic topography" DEM (with resolution similar to that of the photograph) is constructed. This topographic information is used to route water to small channels (usually unresolved on standard topographic maps) on the pavement surface that support most of the vegetation. Estimates of water discharge in these channels are combined with field data to estimate quantitatively the response of vegetation to specified changes in infiltration, climate, or other causes of changes in runoff. A regional riparian response index is derived.

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Forward

This document summarizes results obtained from research on dynamics of desert pavement surfaces.

Desert pavements are extensive geomorphic surfaces often used by the US Army for training (NTC) and testing (YPG). The present project focused on problems associated with desert pavements at Yuma Proving Grounds, AZ, although the results of this study are applicable to pavement surfaces found elsewhere.

One fundamental goal was to determine the response of pavements to human impact. Pavements in their natural state are nearly static features of the landscape (a fact that underlies their stability). The problem is to understand what pavements are likely to do when disturbed in certain ways, for example by vehicular traffic – a type of disturbance quite dissimilar to any natural disturbances for which we might otherwise have field evidence.

A related question is to assess the response of vegetation to changes in surface conditions (such as infiltration rates – which may be modified due to either compaction or loosening by tank and other vehicle traffic).

A key process that determines much of the response of both the pavement surface itself as well as the vegetation is the behavior of surface runoff. Two goals of the work described here were (1) to develop methods that would be suitable for determining the behavior of runoff on pavement surfaces when infiltration rates were changed in prescribed ways, and (2) to estimate the response of flow characteristics in channels and the vegetative response associated with those flow parameters.

Earlier work on pavements has been largely descriptive, or concerned with the soils underlying the pavement surface. The present project instead has focused on understanding the particular hydrologic surface processes that determine pavement behavior, and the relation of vegetation patterns to these processes. This has been accomplished by developing simple dynamical models of pavement evolution using hydrologic and diffusion models, together with field collection of data on the distribution of vegetation.

One key result was the development of new research tools for simulating surface runoff at scales below those available from commonly available topographic maps. This new method, synthetic topography generates high-resolution topographic maps on otherwise smooth, low-relief desert pavement surfaces where only low-resolution data may be available. Effectively increasing the resolution of surface elevations at a small fraction of a meter allows the routing of water over these very level surfaces, thus enabling studies of the water requirements of riparian vegetation. It also potentially provides a way to generate a fine-scale (soldier- or tank-scale) topography that may not be derivable from standard mapping sources.

Information on the distribution of vegetation on the pavement surfaces in our study area was collected by field observation and measurement. Occurrence of this mostly riparian vegetation is strongly correlated with location in the channel (there is little vegetation in the water-poor upper ends of most channels). Estimates of runoff and resulting channel discharge were correlated spatially with occurrence of vegetation to provide an index of vegetative response to land use (or climate change) in the YPG area.

These methods and results are described in the following sections.

Table of Contents.

Statement of Problem Studied.

The problem studied has two parts, (1) to investigate pavement dynamics by developing a method for routing water across almost flat topography cut by many narrow channels, where the topography in question is too subtle and the scale too small to be accessible from standard data bases; and (2) to use estimates of water discharge into these channels as a correlate of vegetation density, and to develop a predictive scheme for assessing the vegetative response to changes in runoff that reflect land use and climate change .

Summary of Results.

The method of synthetic topography (ST) was a key product of the research supported under this grant. Using ST, a low-resolution topographic data set can be effectively transformed into a high-resolution map using our knowledge of the relevant physical processes that affect surface change. The method of constructing such maps is outlined. The work reported here is based on the simulation studies and field work performed at YPG by Peter Haff and graduate students Lesley Glass and Mark Strudley.

The specific application of ST was to an alluvial fan area in Yuma Proving Ground, Arizona, Fig. 1; use of ST is illustrated with data from that site.

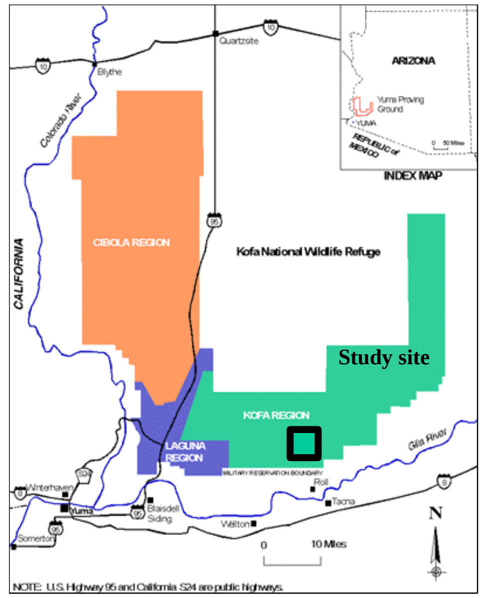

Figure 1. Study area for creation of synthetic topography surface for part of KOFA range at YPG.

With this method, two-dimensional information determined from analysis of aerial photographs, as in Fig, 2a, was converted into elevation data at a resolution that is comparable to the resolution of the photograph. For example, in Fig. 2a, the resolution is

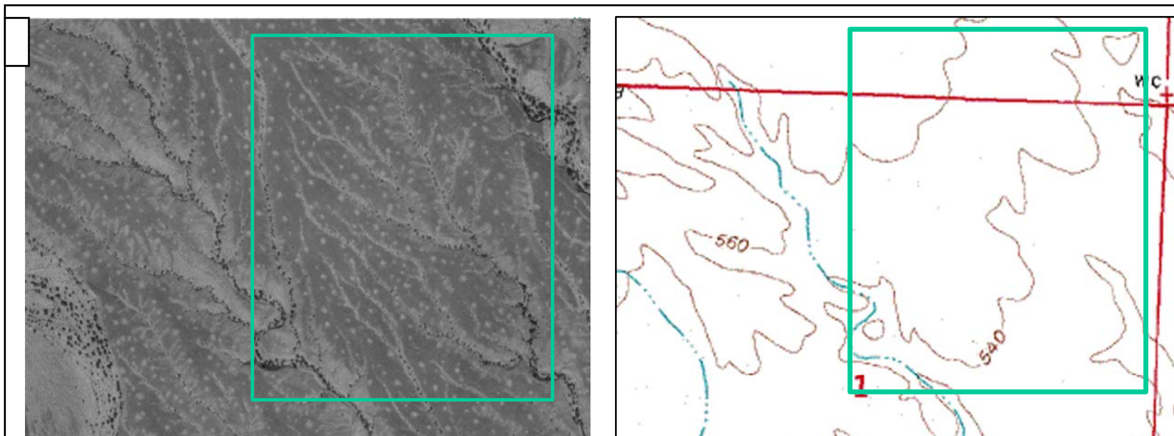

Fig. 2. (a) (left) Areal photograph of study area (rectangle), short dimension of rectangle is about 1km; (b) (right) USGS topographic map of same area. Only the major drainage features are captured in the topographic map. The aim of ST is to combine the aerial photo map with the data from the low resolution map, using process based modeling, to produce a high resolution map that respects all the drainage ways shown in (a). The rectangle outlines the study area.

1m. ST produces a topographic data set of similar resolution. Fig. 2b shows the USGS 7.5’ map of the same area (refer green rectangles), but based on 30m resolution.

For many landscapes, it is possible to use stereo pairs to construct the topographic map directly. For common desert surfaces of the kind represented in the study area at YPG, however, the landscape is so smooth, Fig. 3, and elevation changes over the lateral distances as represented by the resolution of the photographs so small (centimeters), that stereo viewing is often not realistic. Nonetheless, it is these elevation differences that control overland flow. Hydrologic modeling at this resolution thus requires a way to estimate surface elevations over distances (few meters) that are often small compared to the resolution of standard data bases. Here we describe how to construct such high-resolution maps.

Fig. 3. Smooth pavement surface makes numerical hydrologic routing difficult.

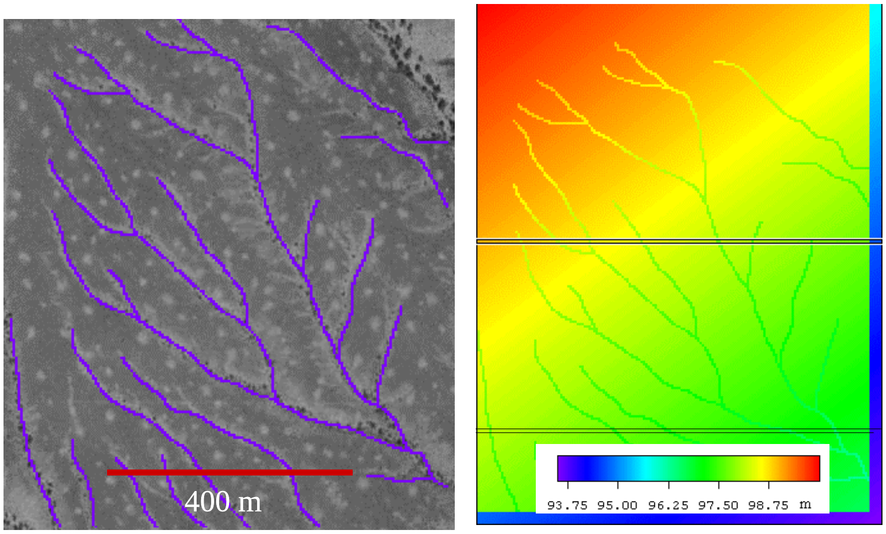

Fig. 4. (a) (left) Principal channels are extracted from the photograph; (b) (right) channel pattern from (a) is projected onto a sloping surface that approximates large scale surface topography, and then each channel is etched slightly, i.e., lowered in elevation, a small amount (small fraction of meter). Relative elevation scale in meters shown in legend. Horizontal lines are position of transects shown in Fig. 5.

The basic idea is to determine the plan view pattern of surface channelization, project this onto a low resolution surface that approximates the real surface topography, "etch" the channel pattern into this low-resolution surface, and then use a process-based model to join these protochannels together with the surrounding interfluves into a surface whose topography is consistent both with channel location and with the action of the physical processes that are thought to characterize this surface.

In the approach developed here, a discrete model of runoff is used, in which units of

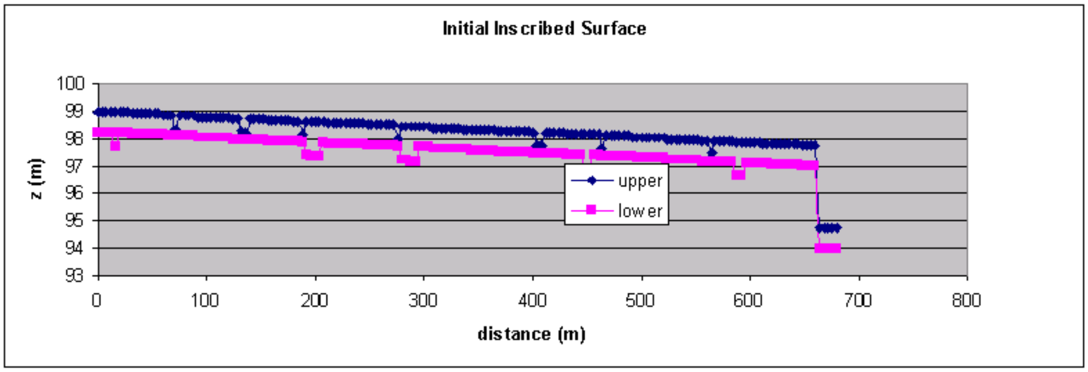

Fig. 5. Elevation along the two transects shown in Fig. 4b, showing channels with artificially steep (vertical) sides impressed or “etched” into a gently sloping approximation to the real pavement surface.

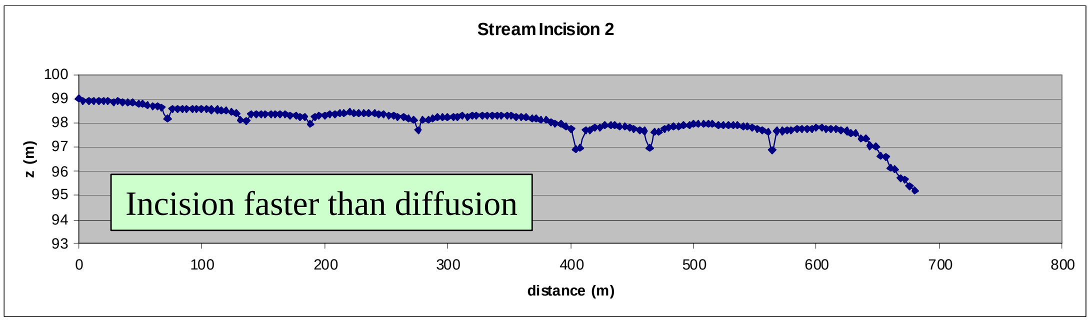

Fig. 6. Elevation along the upper transect of Fig. 4b, showing modification of stream channel depths and interfluve shapes by combination of diffusion plus fluvial incision.

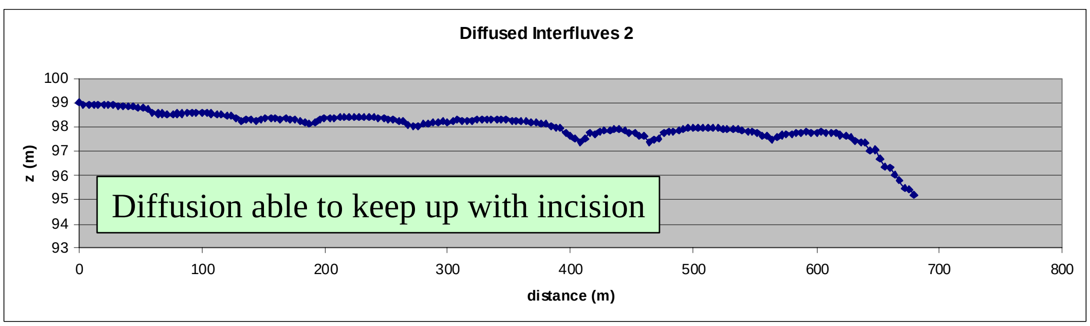

Fig. 7. Same as in Fig. 6, but greater diffusion, keeps all interfluves graded smoothly to channel beds.

water move downslope across the surface, picking up and depositing sediment according to transport rules appropriate for the surface in question. In Fig 4., this process of stream-template projection and channel etching is shown for part of the study area.

Fig. 5 shows the surface elevation along the two transects shown in Fig. 4b.

The next step is to run process models on the surface in order to convert the etched surface into a form that is consistent with the assumptions of the models. Here we look at the effects of two key processes of landscape change, sediment transport by running water, and hillslope diffusion, where mass transport is driven by slope. Fig. 6 shows how the upper profile in Fig. 5 develops under the combined action of incision driven by water flow in the channels, and smoothing of interfluves driven by diffusion. As seen in the field, interfluves become graded toward channels, and channels deepen downslope.

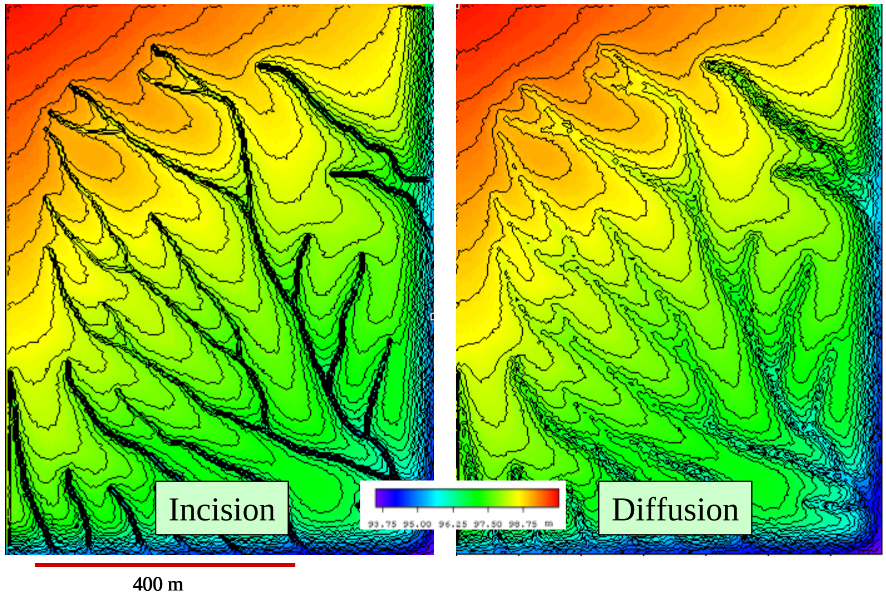

Fig. 8. (a) (left) Synthetic topography corresponding to models used in Fig. 6, with strong incision; (b) (right) Synthetic topography generated by strong(er) diffusion, with steep channel banks smoothed out and interfluves graded to channel beds. Color scale shows elevations.

The detailed shape of the channel cross section depends on the relative strength of incision versus diffusion. In Fig. 6, incision is fast enough that diffusion has not had time to grade the interfluves smoothly all the way to the channel beds. This type of incision is commonly seen in the field at YPG.

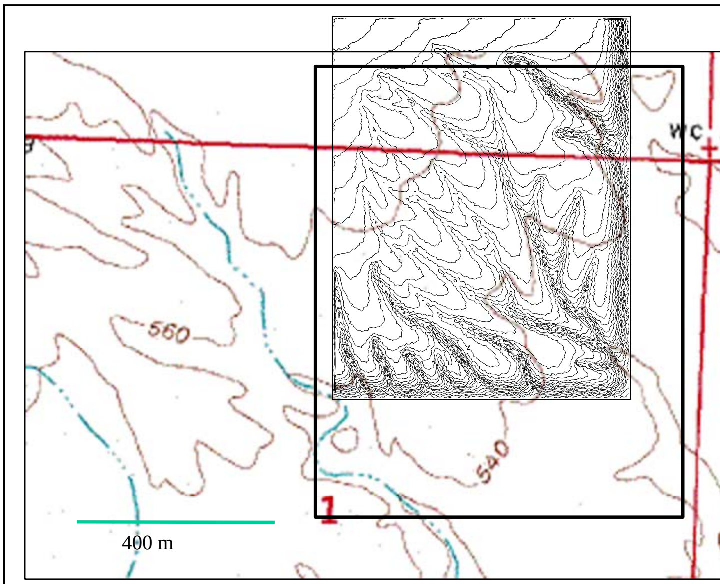

Fig. 9. High-resolution ST contour map overlaid on low-resolution USGS map. Stream channel locations emerge in detail, as do details of interfluve slopes, in the ST model of the surface

Fig. 7 shows the same profile but with a larger diffusion coefficient. Here the interfluves are graded all the way to the channel bed, a relation also commonly seen at YPG.

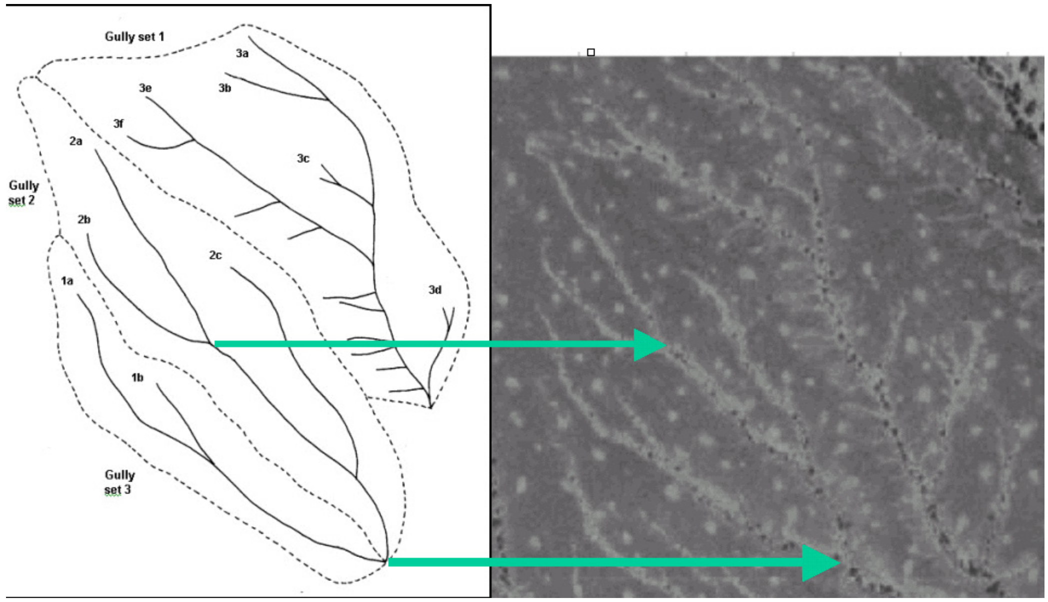

Fig. 10, (a) (left) Schematic of gully pattern at study area; (b) (right) Aerial photograph of gullies in study area with arrows identifying corresponding points in (a). Note labels for gully sets 1 and 3 are reversed in the figure.

Fig. 8 shows topographies corresponding to combinations of these two process models. In each case interfluves are now graded toward streams, but in the left panel strong incision has produced channels with steep banks, while in the right panel with stronger diffusion, interfluves are more smoothly graded to streambeds; in both cases, the streams become more deeply incised with distance downstream.

Evidently different process models give different topographies. In a particular application, physically-based process models are chosen which generate topography that is consistent with our knowledge of the actual terrain. In the case of the YPG study area described here, interfluves are typically smoothly graded to channel beds for the lowest order channels, but become increasingly incised with distance downstream. This pattern is best captured in a combination of runoff-diffusion models similar to that used for the more diffused landscape shown in Fig. 8b.

Finally, we compare visually and directly the landscape map for the study area as generated by ST, with the "original" low resolution USGS map, Fig. 9. The huge increase in resolution is clear. The undulations in the contours of the USGS map are fleshed out into a detailed network of channels. The ST map is consistent with all the undulations in the contour lines of the USGS map, but effectively interpolates the channels and interfluves in much greater detail.

ST can be used for any application where high-resolution measurements of surface topography are lacking, but where one is nonetheless interested in physical processes at small scale. For example, ST, using suitable process models, could be used as part of a

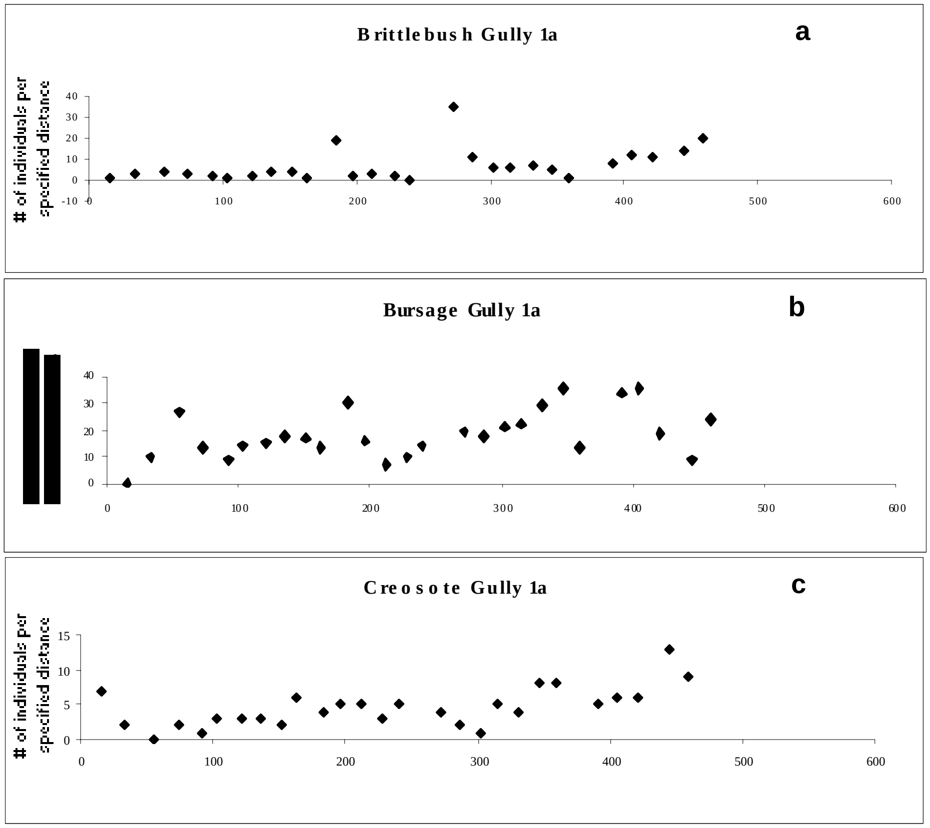

Fig. 11. Vegetation counts versus distance downstream for Gully 1a. Each data point records the number of individual specimens of the given species above that point and below the previous point. Distance scale is in meters, measured downstream from the channel tip.

larger program to generate close-up landscape features, i.e., soldier-scale features, as they would appear to someone on the ground. These would not need to be limited to topography alone, but, if appropriate process models were available, could include vegetation, surface texture, and so on.

Here we sketch how ST could be used to help address a problem of interest to the US Army, namely, impact of changes in land use on vegetation. Vegetation on the alluvial surfaces studied at YPG is mainly riparian, confined to or near the beds of channels such as those shown in the photograph in Fig. 2a. The vegetation is restricted to these locations because of the extreme aridity of interfluve soils. Interfluve infiltration rates are low, with water moving quickly over the bare, smooth desert pavement surfaces into the closest channel. Most vegetation on the pavement surface is confined to channels that are too small to resolve on a low-resolution map such as that in Fig. 2b. ST can be used to create a topographic surface that is consistent with small-scale planview information extracted from aerial photography. The high-resolution ST digital elevation data can then be used to route water across the inter-channel surfaces and down the channels. In the following paragraphs we describe the relation of riparian vegetation, as measured at our study site, to a water availability index correlated with the total discharge of water passing any point in channel.

Fig. 12. Similar to data in Fig. 11, except for two arboreal species. Relative size (height) is indicated by the type of symbol. Species first appear tens to hundreds of meters downstream from gully tip. “Small”, “medium” and “large” designations defined in text.

To give a specific example, consider the sets of channels or gullies indicated in Fig. 10. For convenience of analysis, the gullies are grouped into three sets, 1,2 and 3, as shown in the schematic sketch. Counts of the location and species of perennial shrubs were made in the field. Fig. 11 shows the distribution of brittlebush, white bursage, and creosote as a function of distance from the channel head of the indicated gully. For these xeric species there is a modest increase in shrub density downstream, but specimens are also commonly found right at the channel head, and indeed are sparsely distributed on the interfluves themselves. Shrub size was also measured (not shown here), and an increase in height of typical individuals was documented with increasing downstream distance.

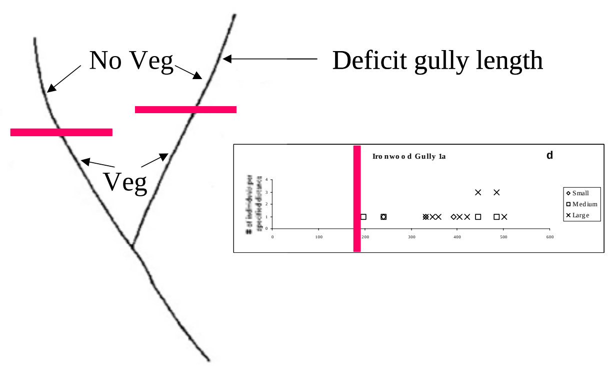

Fig. 13. Definition of deficit gully length (DGL). The inset graph shows how the distribution of vegetation is related to position of DGL. The graph represents distance measured down <u>one</u> of the first order channels, and continuing into the second order channel.

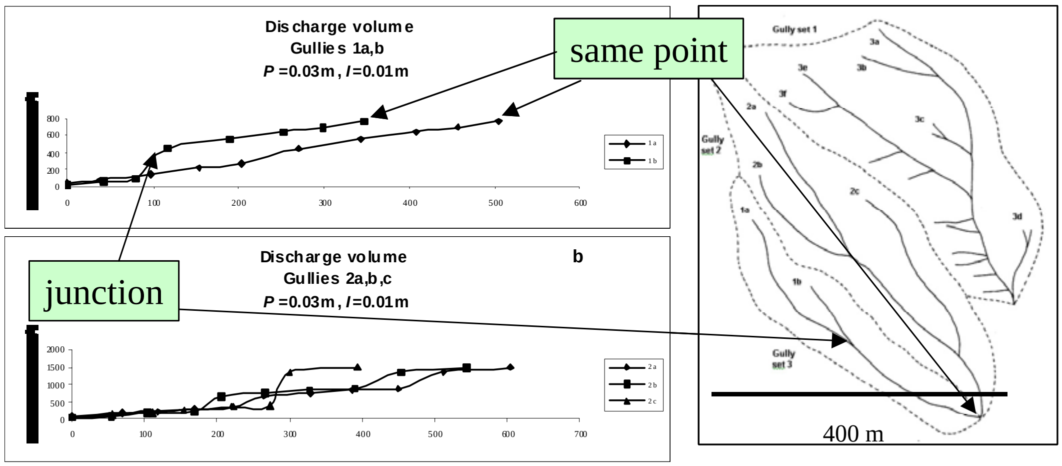

Fig. 14. Left panels plot total stream discharge down the indicated channels, as shown in the right panel, for gully sets 1 and 2. A jump in discharge seen in several of the curves represents water input to that channel from a tributary located at the given distance. The distance in meters is computed from the head of <u>each</u> channel.

The distribution of tree species – ironwood and paloverde – also shows an increase in counts per unit distance in the downstream direction, Fig. 12, but in this case the first specimens only appear a finite distance downstream from the channel head, typically tens to a hundred meters for paloverde, and several hundred meters for ironwood. This offset downstream is taken to reflect water requirements for these riparian species, i.e., downstream distance is a proxy for the availability of water. Too close to the gully tip, and not enough water is available on average to support plant viability.

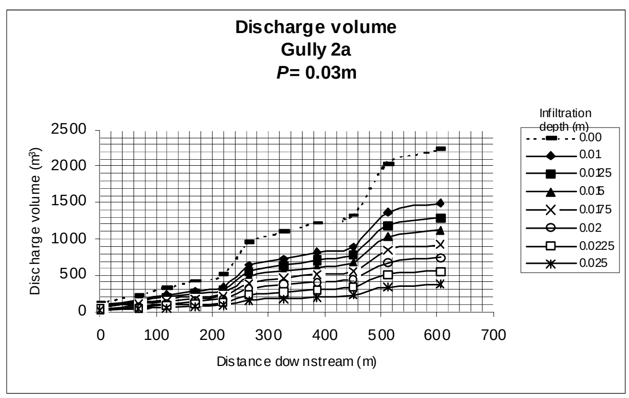

Fig. 15. Illustrative total discharge volumes as function of distance from channel head for nominal rainfall and for different infiltration volumes for gully 2a.

Also shown in the plots in Fig. 12 is tree size, measured in the field as an estimated crown height. Three categories are distinguished: small, medium, and large, corresponding to heights less than 2m, heights between 2m and 5m, and heights greater than 5m. Maximum tree size tends to increase downstream, especially for the largest size trees, the largest ironwoods and paloverdes not appearing until nearly three hundred meters downstream.

The distance from the channel head to the first specimen of a given species of shrub or tree is called the “deficit gully length” or DGL, Fig. 13. The main assumption here is that the DGL will increase under conditions where less water gets into the channel, and decrease when more water is available. In the results reported here we look at how DGL might be expected to increase or decrease under different assumptions about changes in runoff, which in turn is driven by land use or climate change. An increase in the DGL for example implies that riparian biomass – the majority of biomass on the entire surface – is likely to decrease. An estimate of the dynamical response of DGL to changing land (or climate) conditions is thus related to the response of the entire surficial biomass. The simplest assumption is that the pattern of vegetation is shifted downstream by an amount equal to the DGL. Under this assumption, changes in the value of the total riparian biomass can be estimated.

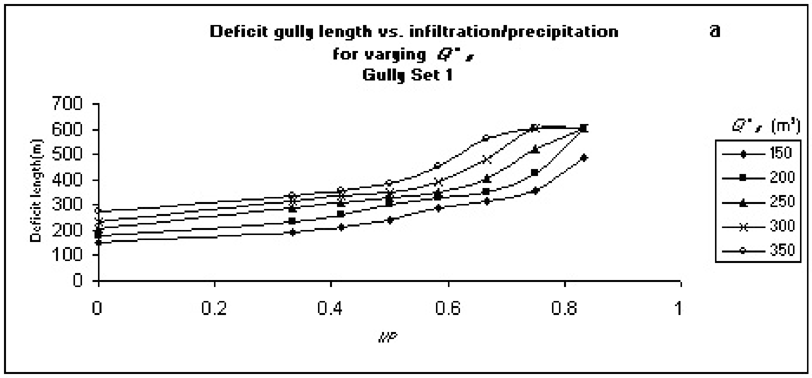

Fig. 16. DGL plotted for gully set 1 vs. relative infiltration, for different values of the critical discharge Q_0. As infiltration rates increase, so does DGL.

Here we provide some examples of DGL response to changes in mean runoff. An analysis of DGL dynamics requires routing of water from the interfluves to the many channels on the surface, for example by ST. Fig. 14 shows the discharge in each stream for gully sets1 and 2 as the result of uniform rainfall and infiltration across the entire study area. A sudden increase in discharge occurs where a given stream is joined by a tributary. As rainfall or infiltration rate change, total discharge also changes. Fig. 15 shows the total discharge down gully 2a for an assumed rainfall of 0.03m and various

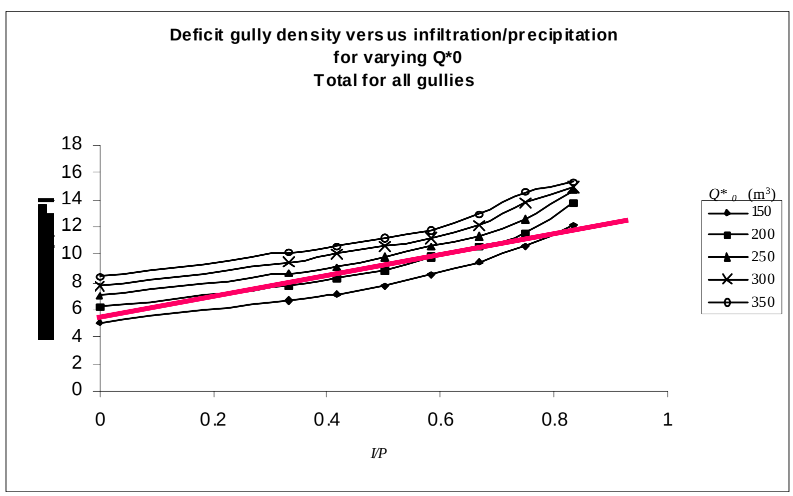

Fig. 17. Deficit gully length density for different values of critical discharge, plotted against relative infiltration rate. Straight line represents trend of DGL density as infiltration increases.

amounts of total infiltration. The numbers here are nominal and meant for illustrative purpose.

While the value of the DGL can be measured directly, the actual effective discharge that produces a particular value of DGL is unknown. This value of discharge is called the critical discharge Q_0. In Fig. 16, plots of DGL versus relative infiltration (infiltration divided by precipitation) are shown for several possible values of critical discharge. Thus the smaller the critical discharge, the shorter the DGL for a given value of infiltration. If the size of appropriate effective storm is known, together with the infiltration properties of the surface, then the critical discharge can be estimated. The values of Q_0 appearing in Fig. 16 correspond to the assumption that intense local thunder cells can deliver several centimeters of rain in a single event, and that it is those events that are most important as water sources for the vegetation. Other assumed meteorological conditions and assumptions about plant water use can be implemented in a similar way.

To put these results in a more usable form, we define the DGL density. This is the total length of DGL in a given area, divided by that area. Fig. 17 shows DGL density versus relative infiltration for varying critical discharge, using information on all gullies analyzed in the study area. A typical value of DGL in this region is $8km^{-1}$, that is, there are about 8 km of gullies lacking vegetation per each square kilometer of surface area.

The slope of the straight line in Fig. 17 is an approximate representation of how DGL density changes with relative infiltration. This relationship suggests that a 20% increase in infiltration at fixed precipitation (or, approximately, a 20% decrease in precipitation at fixed infiltration volume) will lead to an increase of about $2km^{-1}$ in the DGL density. This value can be connected to change in biomass or total population using data such as that shown in Fig. 12. For example, a $2km^{-1}$ increase in DGL density means that approximately two kilometers of riparian vegetation will be lost per square kilometer of surface area. If we take the Fig. 12 data as indicating the presence of about 3 ironwood trees per 100 meters near the downstream end of the deficit gully reach, then the corresponding number of ironwood trees that might be lost due to this change in infiltration (or climate), is about 60 trees per square kilometer. This response has been derived for our particular study plot. However, there is a vast region of YPG with surface geomorphology very similar to the study area. The general methodology used here, and perhaps the values of measured vegetation densities and response index as well, may be applicable over a much larger region. In any case, the ST technique has many applications, the vegetative response discussed here being one of them.

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Lesley Glass
MS Thesis 2000

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